Induced seismicity in geothermal systems: Occurrences worldwide and implications for the Netherlands

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ABSTRACT

Induced seismic events with magnitudes large enough to be felt at the surface are an undesirable potential result of geothermal operations. It is important to understand when and where these events may occur, especially as the number of geothermal systems is expected to increase over the coming years. In order to understand the key factors controlling the occurrence of felt seismicity in geothermal systems an extensive review was performed on many cases worldwide where felt seismicity was reported. In addition, case histories in similar tectonic settings but without felt induced seismicity were included in the review. The review showed that crystalline basement rocks were very prone to seismicity. These rocks are targeted by EGSs, and are often critically stressed. The basement can also be reactivated by pressure perturbations due to geothermal operations in sedimentary layers that are hydraulically connected to the basement. Geothermal fields in tectonically active regions often showed seismicity, but not always of large magnitude. Geothermal systems targeting shallow (<3 km), porous (>15%), low temperature (<100 °C) sandstone aquifers on the other hand have not been associated with felt induced seismicity. These formations are often not very competent, are often far above the basement, hydraulically isolated by clay formations and may have a more stable stress state due to the presence of evaporates or clays. These findings imply that felt seismic events in shallow porous sandstone formations in the Netherlands are unlikely. However, seismicity always remain site-specific and for each case the local geology and its potential to generate seismic events must be considered.

1 INTRODUCTION

Geothermal energy production is on the rise as countries endeavour to meet climate goals and reduce CO_2 emissions. In the Netherlands for example, the number of geothermal doublets for direct-use of heat is expected to increase by more than one order of magnitude over the next decades (Stichting Platform Geothermie et al., 2018). To increase the number of geothermal systems in a safe and sustainable manner and with the support of the local population, it is important to mitigate potential hazards related to geothermal operations. One of these hazards is the occurrence of induced (man-made) seismicity as a result of the reactivation of pre-existing faults and fractures by geothermal operations. This is not bad per se, as for example reactivation of the fracture network leads to an improvement in permeability in an Enhanced Geothermal System (EGS), and most induced events are small and produce ground motions far below the threshold to be felt. However, induced seismicity can become a problem when larger magnitudes occur that can be felt at the surface and/or cause damage to housing and infrastructure. These events are undesirable, and it is important to understand and mitigate the occurrence of larger magnitudes, which is especially important in densely populated areas such as the Netherlands.

Though most of the induced seismic magnitudes were relatively small, some larger magnitude events have been observed in geothermal systems. One of the largest seismic events, probably related to hydraulic stimulation activities for EGS, was a recent M_w 5.4 in January 2018, which occurred 2 months after a series of stimulations of the EGS at Pohang, South Korea (Kim et al., 2018). This event caused widespread structural damage and over 100 injuries. Other well-known events include magnitudes up to M_w 5.0 at the Geysers geothermal field (Majer et al., 2017), a M_L 4.0 at the Hellisheidi geothermal field (Juncu et al., 2018), and a M_L 3.4 in Basel (Häring et al., 2008). In total 37 geothermal cases with M > 2.0 have been listed in the Human Induced Seismicity database (Foulger et al., 2018). To understand when and where induced seismicity occurred we reviewed these cases, and analysed the responsible mechanisms and the dominant key factors for the occurrence of felt induced events. In addition, geothermal case histories in similar areas but where no felt induced seismicity

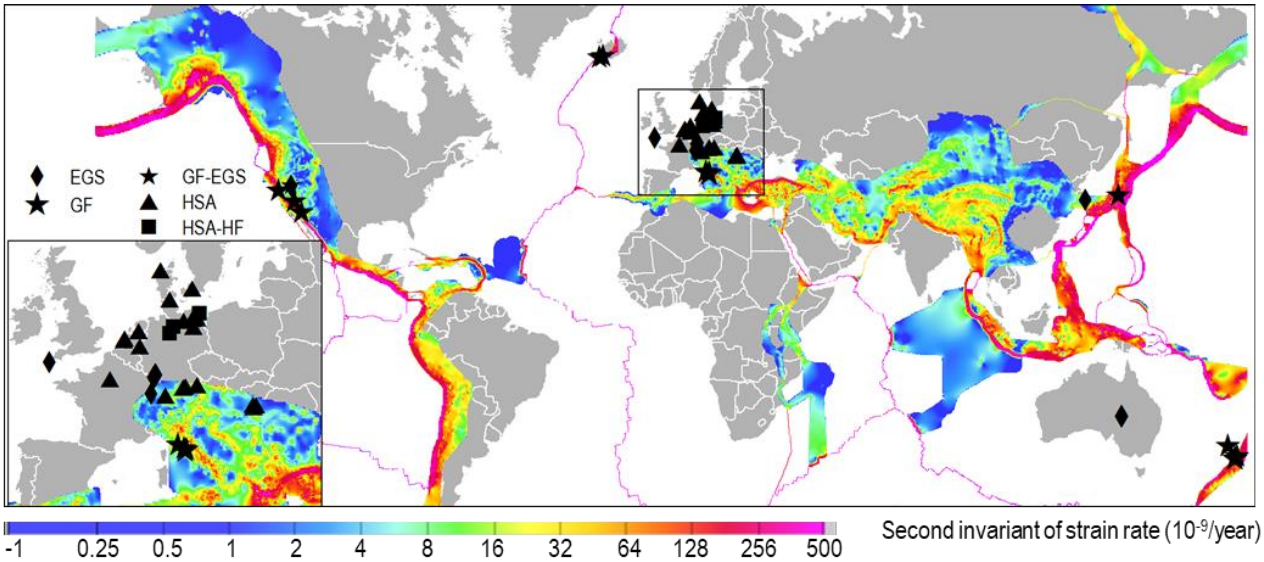

Figure 1 Location of case studies included in the review. Background colors indicate the tectonic loading rate in nanostrains per year (Kreemer et al., 2014).

understand when seismicity does or does not occur. In particular we focused on the effect of lithology on induced seismicity. We give implications of our findings for geothermal systems in the Netherlands, and for geothermal systems worldwide.

2 CASE SELECTION AND KEY FACTOR DESCRIPTION

The selection of case histories was based on the HIQuake database (Foulger et al., 2018). In addition, case histories without recorded seismicity from the same geothermal regions were included. For a case to be selected the information/data should be publically available, e.g. in the scientific literature or public databases. A total of 73 cases were selected, 34 of which were associated with seismicity with M >2.0. These cases were situated mainly in Europe, USA, east Asia and New Zealand (Figure 1, A).

2.1 Geothermal system type

The case histories were divided in three main types: geothermal fields (GF), Enhanced Geothermal Systems (EGS), and hot sedimentary aquifers (HSA).

Geothermal fields (hydrothermal fields) are located in tectonically active regions with or without magmatism, and usually target fractured, high temperature (>200 °C) reservoirs at shallow depth (~3 km up to the surface). Well-known examples include The Geysers (USA), and Larderello (Italy). These systems are the oldest with production of hot water for direct-use <1900, and with first commercial production of electricity in 1926 at Larderello. The fields can be extensive (1 – 10s of km) and contain numerous wells. From the 1970s reinjection of cooled water for waste water injection and/or pressure maintenance became common practice, though not all fields reinject the produced fluids.

The EGS concept was introduced in 1977, following up the Hot-Dry Rock (HDR) concept which was introduced in the early 1970s (e.g. Jung, 2013). In an EGS high-pressure injection stimulates the permeability of the natural fracture network between two wells by shearing, as opposed to tensile fracturing (HDR concept). Since the 1980s a number of pilot-EGS projects have been conducted, and the first commercial plants are operational (Lu, 2018). In this review both HDR and EGS projects are classified as EGS. Note that there may also be EGSs within geothermal fields (GF-EGS), e.g. in the Geysers.

Another type of geothermal systems are low-moderate-temperature (30–150°C) systems in permeable hot sedimentary aquifers (HSA) at relatively shallow depth (<3 km). Typically, water is circulated between two wells (a doublet) at low pressures. Temperatures can be high enough for electricity generation (e.g. near München) but are mostly suitable for direct-use in e.g. district heating, space heating, and various other applications (e.g. North German Basin, Paris Basin, the Netherlands). Hydraulic fracturing within sedimentary aquifers was sometimes conducted (HSA-HF).

2.2 Geological parameters

The following tectonic and geological parameters were retrieved for the various case histories:

- Rock type targeted by the geothermal system
- Distance to crystalline basement
- Φ (%) average porosity
- Stress regime, where NF = normal faulting, NF-SS = transtensional, SS = strike-slip faulting, SS-TF = transpressive, and TF = thrust faulting.
- Tectonic loading rate: The second invariant of the strain tensor (Kreemer et al., 2014), see Figure 1.

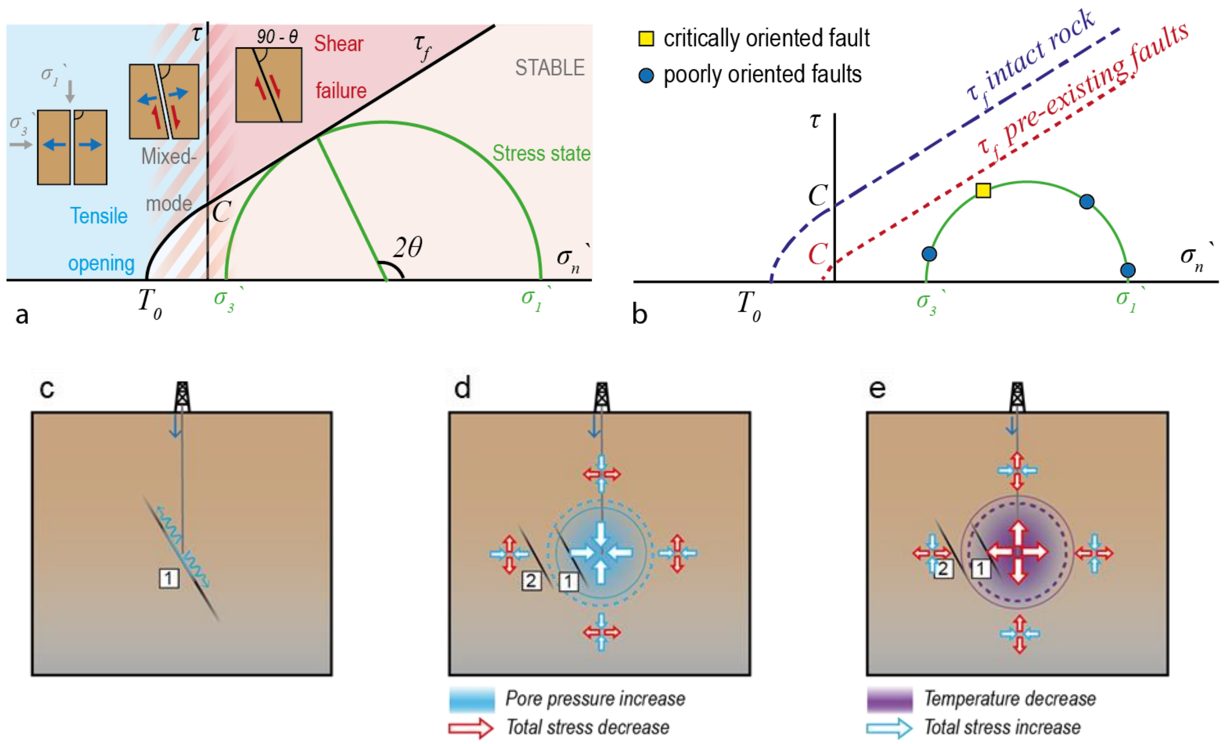

Figure 2 Schematic illustration of the dominant mechanisms of induced seismicity in geothermal systems. A) Mohr Coulomb failure envelop, b) illustration of critically oriented and stable faults. c) Direct pressure increase in faults. d) Poroelastic stressing. E.g. the increase in pore pressure leads to expansion and stressing of the rock mass. C) Thermoelastic stressing. E.g. the injection of cold fluids leads to contraction and stressing of the rock mass.

2.3 Operational parameters

For each activity the following operational data were included:

- Start date and end date (where applicable)
- ΔP (MPa): maximum injection pressure
- ΔQ (l/s): maximum flow rate
- ΔT (°C): temperature difference between reservoir temperature and (re)injected fluids
- ΔV (m^3): the net injected volume

2.4 Seismicity parameters

For each case history the maximum magnitude and the date of occurrence were listed. To avoid bias towards the presence or absence of a local monitoring system, a distinction was made between cases with M ≥ 2.0 (roughly the threshold for seismicity to be felt at the surface) and smaller magnitudes (e.g. Evans et al., 2012). Note that the peak ground velocity controls when events are felt rather than their magnitude, and that this is a function of depth and attenuation as well as magnitude. It may thus be possible that events with M < 2.0 can also be felt.

3 MECHANISMS OF INDUCED SEISMICITY

Geothermal operations lead to pressure and temperature changes in the subsurface, which in turn causes volume changes and stress changes. These stress changes add to the pre-existing tectonic stresses already present in the subsurface. The initial stress may be critical (close to failure), so that only small stress changes are required for reactivation (Figure 2b). When the stress on faults exceeds the failure criterion, fault reactivation can occur which may be seismic, depending on the fault rock behaviour. Here we summarize the dominant stressing mechanisms in geothermal systems.

3.1 Direct pressure increases in faults

Pore fluid pressure changes due to production or (re)injection are the most ubiquitous stress perturbation in geothermal systems. An increase in pressure on a fault due to e.g. fluid injection reduces the effective normal stress on the fault and brings the fault closer to failure. The elevated pressure diffuses away from the injection well as a function of time and space, increasing the pressure and inducing seismic events further away from the source. When injection occurs in a relatively impermeable but fractured rock mass, the fractures dominate fluid flow and diffusion, whereas for porous rocks the matrix is more important in controlling the fluid flow and diffusion. Diffusion of pressure can result in seismicity occurring after injection is terminated, as pressures further away are still increasing. In fact, some of the larger magnitude events in EGSs occurred post shut-in, e.g. at Basel, Soultz-sous-Forêts. At Basel, seismicity continued for several years after shut-in of the well, as pressures diffused further and further from the well (Deichmann et al., 2014).

3.2 Poroelastic stressing

A change in pore pressure causes a change in rock volume, which results in stress changes within the pressurized volume (case 1 in Figure 2d), *and* in the surrounding rock mass – i.e. poroelastic stressing (case 2 in Figure 2d). The magnitude of the stress changes depend on the pressure change, the elastic properties of the rock mass and the geometry of the rock mass experiencing a pressure (e.g. Segall & Fitzgerald, 1998; Soltanzadeh, Hamidreza & Hawkes, 2009; Soltanzadeh, H. & Hawkes, 2008). The example of a spherical pressure increase (e.g. around an injection well) shows the total stresses become more compressive within the pressurized volume. However, due to the direct pressure effect (section 3.1) the effective stresses become smaller and the net effect is a more critical stress state. To the sides of the expanding volume the horizontal stress becomes more compressive, but the vertical stress decreases. The poroelastic stress changes outside of the pressurized volume are smaller than inside the volume, and decay strongly with distance.

Most geothermal fields experience a net pressure decrease, as there is no reinjection or only partial reinjection. Poroelastic stressing due to production resulted in reservoir compaction and subsidence at the Geysers geothermal field (Mossop & Segall, 1997).

3.3 Thermoelastic stress changes

Analogous to poroelasticity, changes in temperature cause volumetric strain of the rock mass, which leads to stress changes within and around the volume experiencing a temperature change. An example for a spherical cooled volume is shown in Figure 2C. The total stress changes are opposite to those resulting from a pressure increase, because cooling leads to a decrease in total stresses. In the normal faulting scenario both faults within and just outside the cooled volume become less stable (Figure 2D). The effect of temperature changes ΔT may be strong, and are related to pore pressure changes ΔP through (Segall & Fitzgerald, 1998)

$$\frac{\sigma^{\mathrm{thermo}}}{\sigma^{\mathrm{poro}}} = \frac{E\lambda\Delta T}{(1-\upsilon)\alpha\Delta P}, \quad [1]$$

where E is Young's modulus, λ is the linear thermal expansion coefficient, ν is Poisson's ratio, and α is Biot's coefficient.

Temperature changes are especially large at reinjection sites in geothermal fields, with ΔT often exceeding 150 °C. Seismicity often clusters around reinjection wells, and thermoelastic stressing may be an important mechanisms causing these events, e.g. at Rotokawa (Sherburn et al., 2015) and the Geysers (Martínez-Garzón et al., 2014; Rutqvist et al., 2015).

4 RESULTS OF CASE HISTORY REVIEW

The occurrence of induced seismicity was analysed in relation to the geothermal system type and rock type, geological and tectonic parameters, and operational parameters.

4.1 Geothermal system type and rock type

EGSs often generated felt induced seismicity, e.g. Basel, Soultz-sous-Forêts (Figure 3a). Most EGS target deep, naturally fractured crystalline basement rocks, with a matrix porosity of <2%. Flow is purely controlled by the fractures and faults, and hydraulic stimulation is required to generate the required permeability. Faults and fractures are also often critically stressed, requiring only small pressure perturbations for fault reactivation and seismicity . Though seismicity was common in EGSs, it was not always of large magnitude; the local fault structure controlled whether large magnitudes occurred. When no large faults were present in the vicinity of the injection well, seismicity may remain limited, e.g. at Jolokia (Baisch et al., 2015).

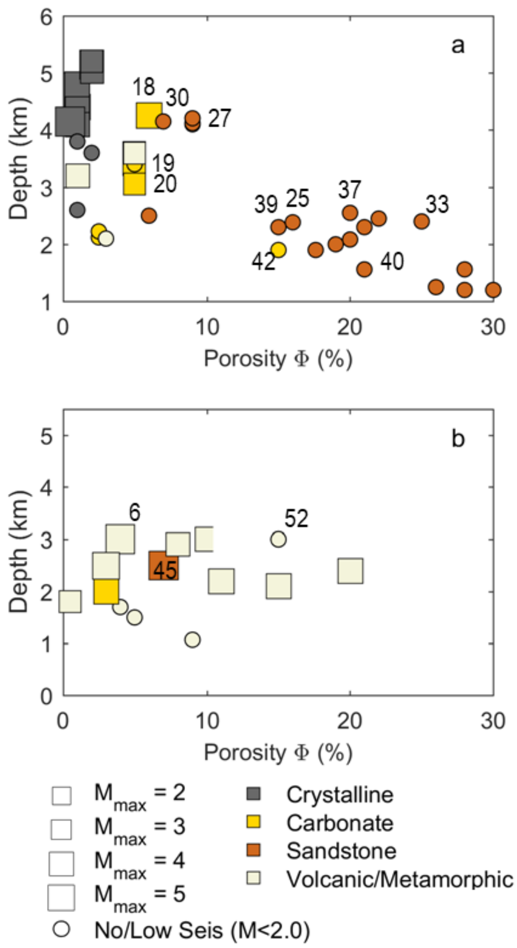

Figure 3 Depth and average matrix porosity of geothermal systems and the occurrence of seismicity. a) hot sedimentary aquifer and EGS, b) geothermal fields. Numbers indicate cases, see Table 1.

Seismicity was occasionally observed in hot sedimentary aquifers (HSA) targeting low porosity (<10%) sedimentary rocks. These rock types include carbonates (e.g. the Molasse Basin) or deeper, tight sandstones (e.g. Upper Rhine Graben) with low matrix porosity but with permeable fractures. Stimulation is often not required, and fluids are circulated at low injection pressures between two or more wells. Despite the low pressures, seismicity may occur. The largest event was a M 3.5 in Sankt Gallen (#18 in Figure 3), which occurred during well control operations. A larger fault structure at depth was reactivated. Several M 2.0 – 2.5 events occurred during circulation at e.g. Unterhaching (#19) (Megies & Wassermann, 2014), Poing (#20) (LIAG, 2018), and at Insheim (Küperkoch et al., 2018). These events occurred in the granitic basement, which was directly underlying the sedimentary aquifer.

No seismicity was observed in the shallower porous sandstone aquifers such as those in the North Germany (e.g. Neuruppin #33), the Netherlands (e.g. Honselersdijk, #25), and Hungary (e.g. Orosháza-Gyopárosfürdő,#40) and porous carbonates such as the oolitic formations of the Dogger in the Paris Basin (#42).

Seismicity in geothermal fields was also common (Figure 3b). The largest magnitudes are M 5.0 in The Geyser (#6), an M 5.1 in Salton Sea (#45), M 4.4 in Coso, and an M 4.0 at Húsmúli in the Hellisheiði field. However, magnitudes are not always large. In geothermal fields in New Zealand the largest magnitude was 3.2 (Rotokawa), but in some other fields no seismicity was recorded (e.g. Ohaaki, #52). Similarly in Iceland some fields did not induce large seismicity, e.g. Krafla). In some geothermal fields there are clear correlations between seismicity rates and injection. In other fields the correlation is not clear, and induced seismicity can be difficult to distinguish from natural seismicity (e.g. Salton Sea).

4.2 Tectonic loading and stress regime

In the previous section it was shown that crystalline basement was prone to felt seismicity. The basement is targeted by EGSs where hydraulic stimulations generate a large number of (micro)seismic events. However, the basement can also be reactivated by stress perturbations caused by geothermal operations in overlying sedimentary layers. For several sites close to the basement seismicity with M > 2.0 was also observed (e.g. Sankt Gallen). Also two sites in the Molasse Basin resulted in M_L 2.1 and M_L 2.4 events which were felt by the public. In both cases the events were located in the basement underlying the geothermal target formation. However, over 20 other sites in the Molasse Basin did not produce felt seismicity, indicating how seismicity can be site specific. No seismicity was reported for geothermal operations in sandstone formations far from the basement (> 1 km).

Most of the larger events (M>4.0) occurred in regions which were tectonically active. However, M < 3.9 events were also observed in tectonically stable regions, e.g. Habanero EGS, Australia. Also the M 5.4 at Pohang occurred in an area with relatively low tectonic loading rates

There was no clear correlation of induced magnitudes with the tectonic regime. Larger events with M > 4.0 occurred both in trans-tensional environment (NF-SS) as well as transpressive (SS-TF) and thrust faulting environments (TF).

4.3 Operational parameters

The operational parameters affect the stress changes in and around a geothermal system.

Most events with M > 2.0 occurred at (re)injection pressures exceeding 10 MPa, for EGS and HAS (Figure 5a). Pressure at the Pohang injection site were largest with 90 MPa. Pressure changes in most HSA were low. For geothermal fields however there was no clear correlation between the (re)injection pressure

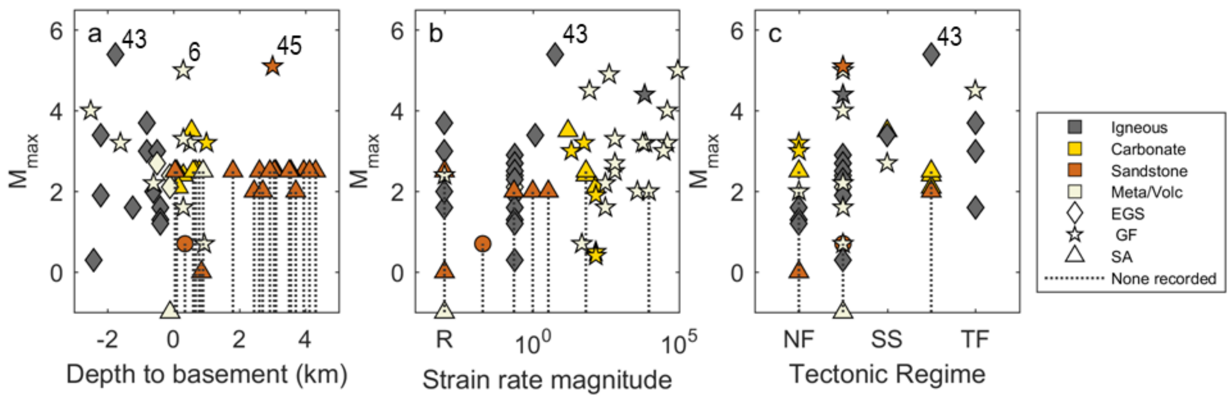

Figure 4 Geologic and tectonic parameters and the maximum magnitudes observed as a result of geothermal operations. a) depth to crystalline basement, b) tectonic loading rates, given as the second invariant of the strain tensor from the global strain rate model by Kreemer et al. (2014) in nanostrains per year. R: regions assumed to be rigid in the model .c) Tectonic regime.

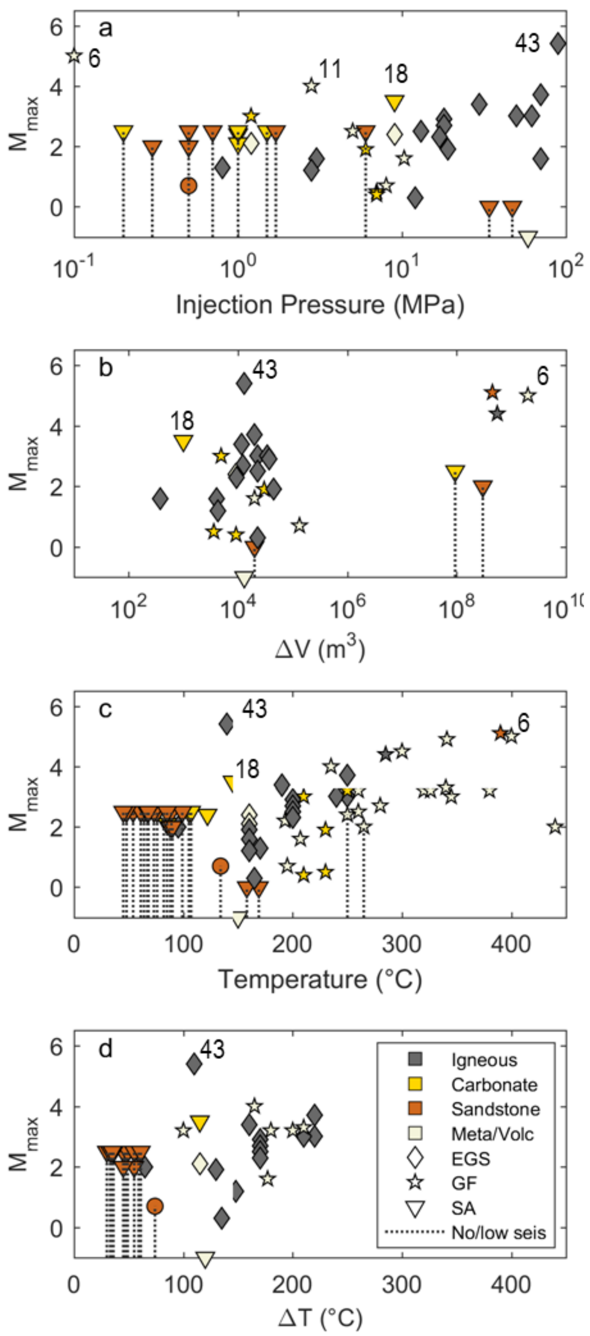

Figure 5 Operational parameters against observed maximum magnitudes at different geothermal sites. A) Injection pressure at the wellhead, b) absolute volume change, c) reservoir temperature, d) temperature change between reinjected fluid and the reservoir.

and the maximum magnitudes. The pressure changes can be relatively small, but the event size may be large. For example, at the Geysers reinjection occurs under gravity drive, and at Húsmúli the reinjection pressure was just 2.8 MPa. However, many other mechanisms are important in geothermal fields, such as poroelastic stressing due to depletion of the geothermal reservoir, or thermoelastic stressing.

There was no clear correlation between the volume change and maximum magnitude. The volume change (injection) of EGSs was 10^3 – 10^5 m^3 whereas for geothermal fields the net volume change (production – injection) could range up to 10^9 m^3. Several larger magnitudes were observed at high volumes, e.g. M 5.1 at Salton Sea, and a M 5.0 at The Geysers. However, at the Pohang site a net volume of only 6000 m^3 was injected, but a similar magnitude event of M 5.4 occurred.

In general, magnitudes increased with increasing reservoir temperature and temperature change (Figure 5 c and d). Seismicity with M > 2.0 only occurred in systems with reservoir temperatures exceeding 100 °C, which is often in granites, metamorphic, and volcanic rocks. The magnitude at Pohang was relatively large compared to EGSs targeting reservoirs at similar pressures.

5 DISCUSSION

5.1 Key factors controlling seismicity

Critically stressed faults play a crucial role for the occurrence of felt induced seismicity. Only small stress changes are required to reactivate these faults, and relatively small injections may cause large events, such as the Pohang M 5.4 event. Reactivation of critically stressed faults did not occur in or near all geothermal systems; mostly reactivation of critically stressed faults was reported for the crystalline basement or in geothermal fields. In other instances without significant seismicity there may be no major faults present near the geothermal system, the in-situ stress may not be critical, or rocks may not be seismogenic.

The crystalline basement was seismogenic and prone to hosting larger magnitude seismic events. These events resulted from stimulation of the basement, or from geothermal operations close to the basement (see e.g. Figure 4a). Flow is controlled by fractures and faults, and pressure changes can migrate to large distances from the well and encounter critically stressed faults. Crystalline rocks are very competent and pressure and temperature changes cause strong poroelastic and thermoelastic stress changes. The largest event related to geothermal operations occurred in the basement, ie. the M 5.4 Pohang earthquake. However, in other cases events have remained limited. This may be the result of the local structural fabric; larger events occurred when larger fault structures were reactivated but events remained small when no major faults were present near the injection well.

Geothermal fields are also often seismogenic, although magnitudes are not always large. The largest magnitudes occurred in the Geysers, Salton Sea, Yanaizu Nishiyama, and Hellisheiði. Mostly events are related to reinjection operations, and in addition to pressure effects, thermal effects may play a large role. In Iceland the injectivity depended strongly on injected fluid temperature. Cooler fluids (ΔT=210 °C) resulted in an improved injectivity because of thermal contraction of the reservoir faults and fractures. Additionally seismic events were measured. It is unclear why events in some geothermal fields remain smaller than in other fields. We recommend a more in depth study of the reservoir stresses and rock types and their propensity for seismic rupture.

No felt seismicity was reported for geothermal systems in porous sandstone formations. Doublets in the Netherlands and North Germany have been producing for years without felt induced seismicity. The pressure change in a typical doublet is smaller than in EGS, but this by itself does not explain the lack of seismicity, since small pressure changes can reactivate critically stressed faults. Thermoelastic stress changes can also be large as temperature changes are significant. One explanation for the lack of seismicity may be that the stress in shallow sedimentary formations can locally be less critical than in the basement. Clay-rich and evaporate-rich formations can relax the differential stresses through viscoelastic creep, leading to a more stable stress state (Sone & Zoback, 2014). The Jurassic and Cretaceous sandstone targets in Europe are often interbedded with claystones, which may have a stable in-situ stress, and could potentially relax stress changes related to geothermal operations. Laboratory experiments show that clay-rich fault rocks tend to deform through stable sliding and are thus unlikely to host large seismic events (e.g. Ikari et al., 2009). Also, the claystones may act as a seal, preventing pressure perturbations to migrate to more seismogenic or critically stressed formations. Salt formations may also act as a seal, and decouple the stress in overlying formations from the more critical stresses in the basement. Around salt domes the state of stress may be near isotropic, as was measured in the geothermal test sites targeting the tight Buntsandstein in Northern Germany. Here, no seismicity was recorded despite the high hydraulic fracturing pressure and sensitive monitoring system (Rioseco et al., 2013). Shallow porous sandstone formations may also be very friable, and can sustain less stress build up; porous sandstones may dissipate a large part of induced strains plastically.

Systems targeting deeper, fractured sediments sometimes generated seismicity with M > 2.0. Mostly, the seismic events did not occur within the fractured sediments, but in the underlying crystalline basement, emphasizing again the role of basement. However, the tight sediments may themselves also be prone to seismicity. The deeper formations are very competent, and laboratory experiments have shown that carbonate faults can be seismogenic. In Sankt Gallen seismicity with magnitudes up to 3.5 occurred during well control operations. The events were located below the well, possibly in a trough in the basement filled with tight Permo-Carboniferous sediments (Diehl et al., 2017). Also at Insheim and Landau some events may have occurred in competent Triassic sediments, although the majority of events occurred in the underlying granitic basement (Küperkoch et al., 2018).

Felt seismicity occurred both in areas of high tectonic loading and in (relatively) stable regions. This observation, and in-situ stress measurements indicate that critically stressed are present everywhere, including the intraplate region (Townend & Zoback, 2000; Zoback & Townend, 2001). Tectonic loading rate, and the occurrence of natural seismicity, may thus not be a good proxy for the local state of stress and the potential for induced seismicity. Stress in sedimentary layers can vary with depth and be locally less critical due to viscoelastic relaxation of certain formations. However, under more rapid loading the stress relaxation may be less, and in that case tectonic loading rate may have an effect on stress.

5.2 Comparison to induced seismicity observed in other antropogenic operations

The role of the crystalline basement is also pronounced in seismicity induced by waste water injection, e.g. in Oklahoma. Here, large volumes of waste water are injected at low pressures into a permeable aquifer overlying granitic basement. Although pressure changes in the aquifer are very small, seismicity rates have increased strongly and several events with M > 5.0 have occurred. Most of the seismicity occurred on critically stressed faults in the basement, similar to the seismicity observed near München. The scale of waste water injection is however much larger than the scale of geothermal operations, so the chance of encountering a fault structure in the basement may be larger.

In general, magnitudes increase with the scale of operations, e.g. the volume change or the activity size (e.g.Foulger et al., 2018) Here such a trend was not observed, but geothermal systems span only a limited range in volume changes/sizes,

5.3 Implications for geothermal systems in the Netherlands

The most targeted formation in the Netherlands are Upper Jurassic and Lower Cretaceous sandstones at 1.5 – 3 km depth with aquifer temperatures up to 100 °C. The aquifers are high porosity sandstone layers, interbedded with claystones and shales. Since 2006 the number of producing systems has increased to 8 in 2018 (www.nlog.nl). No seismicity has been reported for any of these doublets. The seismogenic potential is likely low; the formations are kilometres above the crystalline basement, they are (probably) hydraulically isolated from deeper layers by the presence of clay, and the rocks have a low competency and are very friable. Pressure changes are small (circulation at < 5 MPa) and there is no net volume change. However, temperature changes may be significant and we recommend further research on the related stress changes. In comparable systems targeting porous shallow sandstones (North German Basin, Norwegian Danish Basin, Pannonian Basin) no seismicity was observed, even after decades of production.

Another target is the Slochteren sandstone of Upper Permian age, located at 2 – 3 km depth with temperatures up to 100°C. This is a 50 - 275 m thick formation with porosities of 18 – 20%. Since 2013 four doublets have started operations in the Slochteren formation. The Slochteren Formation is also the reservoir rock of the Groningen gas field, where gas depletion has led to induced seismicity within the reservoir interval (Spetzler & Dost, 2017). The pressure changes in geothermal systems may be smaller than for hydrocarbon production, but thermoelastic stressing may be large. The stress path however is different (i.e. less compressive), and the scale of operations is smaller. We recommend more research into these mechanisms. It is important to avoid known faults within or close-by the geothermal systems targeting the Slochteren.

Two geothermal systems in the South East of the Netherlands, at the eastern side of the Ruhr Valley Graben, target fractured Dinantian carbonates at a depth of 2.1 – 2.5 km and temperatures of 70 – 80 °C. Fluids are circulated through a large fault zone. The seismogenic potential for this target formation is larger; fluid flow is dominated by faults and fractures and stress changes may perpetuate to depth. The Dinantian carbonates are very competent, and may have seismogenic friction properties. Also the Devonian underburden is very competent; at this location quartzites may be found below the doublets which are very strong and prone to seismic behaviour. In fact, a number of seismic events, including a M 2.0 event, were recorded near the doublets. The relation with geothermal operations is still under review. In Belgium the same Dinantian carbonates were targeted at the other side of the Ruhr Valley Graben; also here seismic events up to M 1.9 occurred, indicating that (small magnitude) seismicity is expected when this geothermal target formation is exploited. However, the geology of the Dinantian may be spatially variable and each site must be analysed separately

Other potential targets include Tertiary sandstones (no doublets yet) and Buntsandstein (1 doublet).

The occurrence of induced seismicity is always site-specific, and may never be fully excluded. However, we showed that in certain geologic / tectonic settings seismicity the potential for induced seismicity is low. It is important to characterize the local geology and structural settings near future doublets, assess the state of stress where possible, and perform microseismic monitoring where necessary.

6 CONCLUSIONS

A case history review of geothermal systems with or without associated induced seismicity has led to the following findings:

- Large critically stressed faults play a key role in hosting relatively large events, which are induced by relatively small pressure or stress changes.
- The crystalline basement often contains critically stressed faults and operations within the basement have frequently led to felt induced events. However, events may remain of limited magnitude when no large fault structures are present near the geothermal system.
- Geothermal operations within sediments overlying crystalline basement may also lead to felt seismicity when a hydraulic connection (e.g. a fault) to depth exists.
- Competent rocks like carbonates, quartzites, tight sandstones can also host seismic events; they can sustain high initial stresses and may be frictionally unstable.
- High pressure and temperature changes can increase the potential for induced seismicity. However, circulation at low pressures can induce felt events when a connection to critically stressed faults exists.
- Circulation in shallow porous sandstones has low potential for inducing felt events. The sandstone aquifers are often interbedded with compliant clay formations which act as a hydraulic seal and may cause a more stable state of stress. Pressure changes are small, and the competency of the sandstone aquifers is often low. To date no felt seismicity has been reported for shallow porous sandstone aquifers.
- Tectonic loading rate is not a good proxy for the occurrence of felt seismicity. Relatively large events may occur in stable region. Knowledge of the local state of stress and presence of major, critically stressed faults is of higher importance.
- Induced seismicity is always site-specific, and depends strongly on the local geology, stress, and fault fabric.

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Table 1 Overview of case histories. With d: depth (km), T: reservoir or aquifer temperature (°C), dT: temperature difference between (re)injected fluid and reservoir temperature, db: depth of the basement (km), Φ: average matrix porosity, M: maximum magnitude (NR = no seismicity reported), dV_net: net injected (positive) or produced (negative) volume, dP: maximum injection pressure.

	case	region	type	d	T	dT	rocktypy	db		start	M	dV_net	dP_i	tectonic
1	Habanero 1 2003	Cooper Basin	EGS	4.4	250	220	Granite	3.6	0.01	7-11-2003	3.7	2.0E+04	70	TF
2	Habanero 1 2005	Cooper Basin	EGS	4.4	250	220	Granite	3.6	0.01	10-9-2005	3	2.3E+04	62	TF
3	Habanero 4 2012	Cooper Basin	EGS	4.1	240	210	Granite	3.6	0.01	14-11-2012	3	3.4E+04	50	TF
4	Jolokia	Cooper Basin	EGS	4.8			Granite	3.6	0.01	23-10-2010	1.6	3.8E+02	70	TF
5	Rosemanowes	Cornwall	EGS	2.6	95	65	Granite	2			2			
6	The Geysers	Geysers	GF	3.0	400		Metamorphic	3.3	0.04	1-1-1960	5	-2.0E+09	0.1	NF-SS
7	Coso	Great Basin	GF	3.5	285		Crystalline			1-1-1987	4.4	-5.5E+08		NF-SS
8	Brady Hot Springs	Great Basin	GF-EGS	1.8	193		Metamorphic	1.2	0.01	1-1-1920	2.2			NF-SS
9	Desert Peak EGS 2013	Great Basin	GF-EGS	1.7	207	177	Metamorphic	2	0.04	15-1-2013	1.6	2.0E+04	10.3	NF-SS
10	Desert Peak EGS 2011	Great Basin	GF-EGS	1.1	195		Metamorphic	2	0.09	1-4-2011	0.7	1.3E+05	8	NF-SS
11	Hellisheidi	Iceland Volcanic Zones	GF	2.5	235	165	Basalt	0	0.03	1-9-2011	4		2.8	NF-SS
12	Nesjavellir	Icelandic Volcanic Zones	GF		380		Basalt			1-1-1987	3.2			
13	Svartsengi	Icelandic Volcanic Zones	GF	2.0	260	180	Volcaniclastic	0.4		1-1-1976	3.2			NF
14	Reykjanes	Icelandic Volcanic Zones	GF		345		Volcaniclastic			1-1-2006	3			NF
15	Krafla	Icelandic Volcanic Zones	GF	2.1	440		Basalt	2.1		1-1-1977	2		0.3	NF
16	Laugarnes	Icelandic Volcanic Zones	GF											
17	Yanaizu Nishiyama	Japan	GF	2.6	341		Volcaniclastic			1-5-1995	4.9			
18	Sankt Gallen	Molasse Basin	HSA	4.3	145	115	Carbonate	4.8	0.06	19-7-2013	3.5	1.0E+03	9	SS
19	Unterhaching	Molasse Basin	HSA	3.4	122		Carbonate	3.7	0.05	1-10-2007	2.4	0.0E+00	1	TF-SS
20	Poing	Molasse Basin	HSA	3.1	85		Carbonate	3.2	0.05	1-12-2012	2.1	balanced	1	TF-SS
21	Geinberg	Molasse Basin	HSA	2.1	105		Carbonate	2.9	0.03	1-1-1980	NR	balanced		TF-SS
22	Geinberg	Molasse Basin	HSA	2.2	105		Carbonate	2.9	0.03	22-12-1998	NR		0.2	TF-SS
23	Pullach	Molasse Basin	HSA	3.4	107	45	Carbonate	3.5	0.05	1-1-2006	NR	balanced	1.5	TF-SS
24	Californië CWG	Netherlands	HSA	2.1	82	47	Carbonates & SAndstones	3	0.03	20-1-2013	NR			
25	Honselersdijk	Netherlands	HSA	2.4	89	59	Sandstone	6.5	0.16	8-5-2012	NR	balanced		
26	Koekoekspolder	Netherlands	HSA	1.9	76	45	Sandstone	4.5	0.18	10-9-2011	NR	balanced		
27	Gross Schoenebeck water-frac	North German Basin	HSA-HF	4.1	150	120	Volcaniclastic	4	0.09	9-8-2007	-1	1.3E+04	58.6	NF-SS
28	Gross Schoenebeck 4120 gel	North German Basin	HSA-HF	4.1	150	120	Sandstone	4	0.09	18-8-2007	NR	5.0E+02	49.5	NF-SS
29	Gross Schoenebeck 4120 gel	North German Basin	HSA-HF	4.2	150	120	Sandstone	4	0.09	19-8-2007	NR	5.0E+02	38	NF-SS
30	Hannover GeneSys waterfrac	North German Basin	HSA-HF	4.2	169		Sandstone	5	0.07	23-5-2011	NR	2.0E+04	47	NF
31	Horstberg GeneSys	North German Basin	HSA-HF	4.2	158		Sandstone	5	0.07	23-10-2003	NR	2.0E+04	34	
32	Neubrandenburg	North German Basin	HSA	1.2	54		Sandstone	5.5	0.3	1-1-1989	NR			
33	Neuruppin	North German Basin	HSA	2.4	64		Sandstone	5.5	0.25	1-1-1987	NR			
34	Neustadt-Glewe	North German Basin	HSA	2.5	99	49	Sandstone	5.5	0.22	1-1-1994	NR		0.5	
35	Waren	North German Basin	HSA	1.6	61	30	Sandstone	5.5	0.28	1-1-1985	NR			
36	Sonderborg	North German Basin	HSA	1.2	48	36	Sandstone	3	0.28	1-1-2013	NR			
37	Margretheholm	Norwegian Danish Basin	HSA	2.6	73	55	Sandstone	2.6	0.2	1-1-2005	NR		6	
38	Thisted	Norwegian Danish Basin	HSA	1.3	45	33	Sandstone	4.8	0.26	1-1-1984	NR		1.7	
39	Hódmezővásárhely	Pannonian Basin	HSA	2.3	90	55	Sandstone	6	0.15	1-1-1954	NR		0.3	TF-SS
40	Orosháza-Gyopárosfürdő	Pannonian Basin	HSA	1.6	88	45	Sandstone	4	0.21	1-1-2011	NR		0.5	TF-SS
41	Szentes	Pannonian Basin	HSA	2.3	90		Sandstone	5	0.21	1-1-1958	NR	3.0E+08		TF-SS
42	Paris Basin Average	Paris Basin	HSA	1.9	67		Carbonate	2.5	0.15	1-1-1970	NR		1	NF
43	Pohang (PX-1 + PX-2)	Pohang Basin	EGS	4.2	140	110	Granodiorite	2.4	0.01	29-1-2016	5.4	1.3E+04	89.2	TF-SS
44	Uniejow	Polish Lowlands	HSA	2.0	68	35	Sandstone	5.5	0.19	1-1-2001	NR		0.7	
45	Salton Sea	Salton Sea	GF	2.5	390		Sands & Shales	5.5	0.07	1-1-1986	5.1	-4.5E+08		NF-SS
46	Rotokawa	Taupo Volcanic Zone	GF	2.2	340	210	Volcaniclastic	2.5	0.11	1-1-1997	3.3			
47	Kawerau	Taupo Volcanic Zone	GF	2.1	320	200	Metamorphic	2.6	0.15	1-1-1957	3.2			
48	Mokai	Taupo Volcanic Zone	GF	2.4	326	100	Volcaniclastic		0.2	1-1-2000	3.2			
49	Ngatamariki	Taupo Volcanic Zone	GF	3.0	280		Volcaniclastic		0.1	1-1-2013	2.7			SS
50	Wairakei-Tauhara	Taupo Volcanic Zone	GF	2.9	260		Various		0.08	1-1-1958	2.5		5	
51	Ngawha	Taupo Volcanic Zone	GF	1.5	250		Metamorphic		0.05	1-1-1998	NR			
52	Ohaaki	Taupo Volcanic Zone	GF	3.0	265		Volcaniclastic		0.15	1-1-1988	NR			
53	Monte Amiata Piacastl.	Tuscany-Latium	GF	3.5	300		Metamorphic			1-1-1969	4.5			TF
54	Larderello circulation	Tuscany-Latium	GF	2.0	250		Carbonate	3	0.03	1-1-1905	3.2			NF
55	Torre Alfina RA1	Tuscany-Latium	GF	1.7	210		Carbonate			27-1-1977	3	4.9E+03	1.2	NF
56	Latera Well L2 test	Tuscany-Latium	GF	1.5	230		Carbonate			15-3-1980	1.9	3.0E+04	6	
57	Latera L1 test 1981	Tuscany-Latium	GF	1.7	230		Carbonate			22-6-1981	0.5	3.6E+03	7	
58	Latera L1 test 1982	Tuscany-Latium	GF	1.7	210		Carbonate			2-2-1982	0.4	9.2E+03	7	
59	Basel	Upper Rhine Graben	EGS	4.8	190	160	Granite	2.6	0.01	2-12-2006	3.4	1.2E+04	29.6	SS
60	Soultz-sous-Forêts GPK3 2003	Upper Rhine Graben	EGS	5.1	200	170	Granite	1.4	0.02	27-5-2003	2.9	3.7E+04	18	NF-SS
61	Soultz-sous-Forêts GPK4 2005	Upper Rhine Graben	EGS	5.2	200	170	Granite	1.4	0.02	7-2-2005	2.7	1.2E+04	18	NF-SS
62	Landau	Upper Rhine Graben	EGS	3.2			Multiple	2.7	0.01		2.7			
63	Soultz-sous-Forêts GPK2 2000	Upper Rhine Graben	EGS	5.0	200	170	Granite	1.4	0.02	30-6-2000	2.5	2.3E+04	13	NF-SS
64	Insheim stimulation	Upper Rhine Graben	EGS	3.6	160		Multiple	3.5	0.05	7-4-2010	2.4	9.0E+03	9	NF-SS
65	Soultz-sous-Forêts GPK4 2004	Upper Rhine Graben	EGS	5.2	200	170	Granite	1.4	0.02	13-9-2004	2.3	9.3E+03	17	NF-SS
66	Insheim production	Upper Rhine Graben	EGS	3.6	160	115	Multiple	3.5	0.05	13-10-2012	2.1	balanced	1.2	NF-SS
67	Soultz-sous-Forêts GPK1 1993	Upper Rhine Graben	EGS	3.6	160	130	Granite	1.4	0.02	1-9-1993	1.9	4.5E+04	19	NF-SS
68	Rittershoffen GRT-1 hydraulic stimulation	Upper Rhine Graben	EGS	2.6	160		Granite	2.2	0.01	27-6-2013	1.6	4.1E+03	3	NF
69	Rittershoffen circulation	Upper Rhine Graben	EGS	2.6	170		Granite	2.2	0.01	1-9-2016	1.3	0.0E+00	0.8	NF
70	Rittershoffen GRT-1 thermal stimulation	Upper Rhine Graben	EGS	2.6	160	148	Granite	2.2	0.01	23-4-2013	1.2	4.2E+03	2.8	NF
71	Soultz-sous-Forêts GPK2 1995	Upper Rhine Graben	EGS	3.8	165	135	Granite	1.4	0.01	16-6-1995	0.3	2.3E+04	12	NF-SS
72	Bruchsal	Upper Rhine Graben		2.5	134	74	Sandstone	2.85	0.06	1-1-2002	NR	0.0E+00	0.5	NF-SS
73	Vierpolders	West Netherlands Basin	HSA	2.1	85	61	Sandstone	5	0.2	23-9-2015	NR			